Smart Grids

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Contents

1 Electric Power Systems Structure

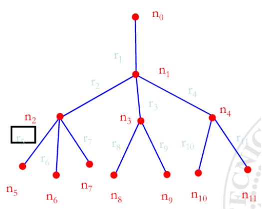
Electric Power Systems can be divided into different subsystems:

- Production. The electric power production is performed in generation plans by using different types of energy (chemical, solar, winds, ...)
- Transmission. The transmission system is composed by sets of high voltage power lines (220V, 380kV) to carry the electric power from the plants to the load centers.
- Distribution. The distribution system is made of a set of high, medium and low voltage to transfer the power form load centers to the end users. To transform the level of transmitted energy, transformer stations are used, together with the sorting stations, which allow to connect different powerlines to the same voltage levels.
- Utilization. The utilization is the set of equipment and electrical consumption devices converting electrical energy into other forms.

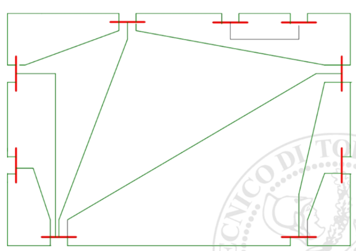
Regarding the production systems, the traditional solution is the *centralized* one. Centralized means that few power plants located in the most suitable sites generates power at MV. A HV transmission systems connect the plants with the aggregated loads and the users are reached by distribution backbones. With this approach there is a distinct role between the consumers and producers.
With the usage of ICT, the system has seen a shift from the centralized one to the *distributed* one. In this way there are many small power generators at MV and LV. The control is distributed and the users' role is changed from the producers/consumers to the *prosumers*.

Regarding the network, there are two basic structures:

- Radial. It is possible to reach any node starting from any other by following a path made of a subset of the lines in the system.



- Meshed. It is possible to reach any starting node from any other following at least two distinct pathways.



2 Communications in Smart Grids

A smart grid is an upgraded electricity network that will incorporate digital technology to improve reliability, security and efficiency of the system through information exchange and storage sources. The infrastructure of a smart grid is the power grid, then there s the addition of others things making it smarter. The main ideas are 2:

- ICT integrated in power grids, such as digital metres to perform a continuous monitoring and control. This requires a wireless network in which a central station processes the collected data from sensors and send the to users.

- With the birth of prosumers, the energetic communication system has switched from monodirectional and centralized to bidirectional. The energy delivery network is able not only to monitor the electricity flow, but also to respond and adapt the flow to customers' preferences and needs.

The main tasks of a smart grid are identifying and resolve faults on power grids (thanks to monitoring), monitoring the power quality and regulate the voltage to help the consumers to optimize their energetic consumption.
By considering the massive ICT usage, cyber security is required to prevent malicious attacks. The smart grids benefits can be achieved by deploying a good Smart Grid Communication Network (SGCN).

2.1 SGCN

A SGCN supports:

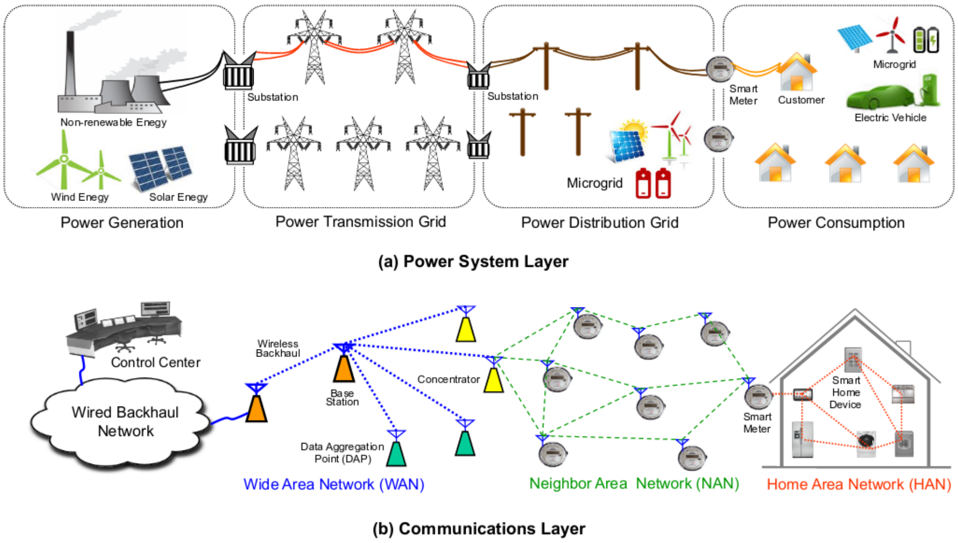
- Advanced Metering Infrastructure (AMI). It is an architecture for automated 2-way communication between a Smart Utility Meter (SMU) IP-based and an utility company. It is an informative infrastructure working with relative energy consumption data. The reports are delivered every 4-hours containing data collected every 15 minutes. It requires up to 10 Kbps bandwidth and this kind of traffic is called 'Meter Reads'. Another kind of AMI traffic is the 'Demand Response' (DR) one. During peaks demand periods, utilities use this traffic to make customers tuning their energy consumption.

- Electric Vehicles. Nowadays this functionality is not fully developed, but it consists on using the vehicles as energy stores

- Wide Area Situational Awareness (WASA). It is used to manage critical structures by preventing them from cyber attacks or by managing emergency situations. They are based on synchrophasors, which are time-synch numbers representing the magnitude and the angles of a sinusoidal signal (phasor). To estimate these values, the Phasor Measurement Unit (PMU) are used. The required bandwidth for the synchrophasor traffic is almost 100 Kbps.
  Another kind of traffic is the "substation SCADA", it is a 4 s interval polling by the master to the intelligent devices of the substations (transit devices between different power grids). Each site has video surveillance which requires few Mbps of bandwidth.

- Distributed Energy Resources. At the periphery of the network where it is more dense.

To monitor and control the network the Fault Location, Isolation and Restoration (FLIR) is used. The optimization traffic allows to increase the users' power quality by reducing the cost.
The typical power grid architecture is:



2.2 Home Area Networks (HAN)

HAN is a network in which devices communicate within a small range, such as a house. A HAN can provide enhanced capabilities which improves the quality of life. HAN devices can communicate not only through wifi, but also with ZigBee. The main advantage of ZigBee is that devices with limited capabilities are better addressed. The HAN technology can provide real-time data about power consumption of users. With HAN technology it possible to engage Demand Response and improving the power optimization.
The main HAN challenges are the consumer data privacy and the data tsunami, or the large amount of data which can help also customers without meters or without paying for it.

2.3 Neighborhood Area Network (NAN)

The NAN is a wireless mesh network able to collect different data coming from different HANs and sends them to the WAN concentrators. The NAN is the most critical segment from a cyber security point-of-view. The main challenge and advantage of NAN is the scalability, however the link condition and the network configurations are extremely time-varying due to multipath. The issues are QoS, Multicasting, routing, etc.

3 ZigBee

ZigBee is a low-cost, low-power, wireless mesh network use to create PAN (Personal Area Network) or HAN. Together with ZigBee, the others two PAN/HANs standards are wifi and bluetooth.
ZigBee is characterized by a low power consumption (30 mA in Tx v.s. 400+ mA in Tx of other protocols). This leads to longer battery life. Regarding the cost, it is the 25% of the Bluetooth one.
Regarding the protocol, ZigBee is at high levels (3-7), so it is directly above the MAC layer. It works with two bands of operation: 868/915 MHz for 24/40 Kbps and 2.4GHz for 250 Kbps. The high frequencies are related to transmission problems.

3.1 Nodes

This technology allows 3 kinds of nodes:

- Coordinator. The coordinator node establishes the network. It searches for an available channel (available means free from other PANs). Once the channel is found, it assigns an ID to the PAN and sends boradcast beacon request frame on remaining channels. In this way it is possible to scan the network by receiving other PAN IDs and to let the nodes of other PANs know that a new PAN is created.
  To perform these operations, the coordinator cannot go to sleep.

- Full Function Device (FFD). This node can participate in any topology can be the PAN coordinator and can talk to all the other nodes.

- Reduced Function Device (RFD). It is limited to a star topology, it cannot be a network coordinator and can talk only to one of them.

The nodes association is performed through a PAN scanning, the association request frame sending and the association response reception.
Regarding the possible topologies, there are three of them:

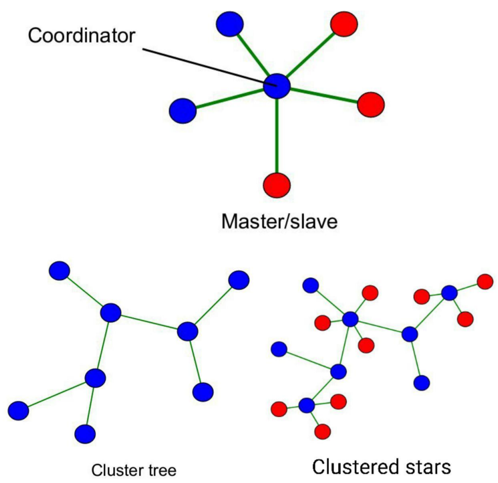


Figure 1: Red nodes are RFD, blue nodes are FFD

3.2 MAC Overview

ZigBee uses CSMA-CA channel access and provides reliable service tanks to the ACKs retransmission. The security is provided by the AES-128.
There are 4 MAC frame types (Beacon, Data, ACK frame and MAC command) and 2 MAC modes:

- Beacon-disabled, or pure CSMA
- Beacon-enabled, or CSMA with optional superframe. This superframe is composed by the beacon sent by the coordinator for synchronization, CSMA period, GTS period and inactive period for sleep modes.

When the beacon is used, the coordinator can modify the request to send data to a node. The node listens to beacon, synchronizes itself with the coordinator and sends data. To reduce latency, the Guaranteed Time Slots (GTS) are used. A portion of the frame is assigned to a device for its exclusive use. When a node wants to communicate to the coordinator, it sends a GTS request, the coordinator replies with a beacon and assigns one of the 7 available GTS to it.

3.3 Data Services

There are 2 ways to transfer data:

- Direct Data Transfer (DDT). It is used for node-node communication or node-coordinator one. The Tx sends a communication request at higher layer, this request is forwarded to the Tx MAC layer. Then the dataframe is sent to the Rx MAC layer. If the ACK is requested, it is sent back to the Tx MAC layer and a confirm is sent to the Tx higher layer. Finally the data is sent to the Rx higher layer.
- Indirect Data Transfer (IDT). It is used to the coordinator-node (and vice-versa) communication. The coordinator has to send data to a node, so the MAC layer sends a beacon to the device (MAC layer too), notifying that there is data for it. The nodes replies with a data request message. After that the coordinator sends an ACK and the data. This is forwarded from the Rx MAC layer to the higher layer and the an ACK is sent back to the Tx MAC layer.

Another kind of traffic is the *polling*. With polling the coordinator checks the status of the devices not responding and the devices ca request if any data is stored in the coordinator and receive it.

3.4 Network Layer

The routing is based on the Ad hoc On Demand Distance Vector (AODV) protocol. It is used for large networks and relies on the UDP protocol. Nodes are addressed by IPs. Each node has a routing table (a source node is associated to a destination node) and a sequence number which is increased with time and is used to check the "freshness" of the routing information.
The advantages of the protocol are (1) the reduced memory requirements, (2) scalability and (3) loop-free routes thanks to the sequence numbers.

3.4.1 Route Discovery

When a source node needs to reach a destination node, it broadcasts a RREQ message. Intermediate nodes receiving RREQ updates their routing tables. Nodes can send back a RREP message (unicast) to the source. The RREP is generated if the node is the destination itself or if it has a valid routing table for the destination. When the RREP crosses the network, intermediate nodes update their routing tables.
An error message (RERR) is broadcasted to the network if a link is broken (destination is no longer reachable), if an RERR message is received from a neighbor of if a node receive a packet for an unreachable destination (no routing table).

3.4.2 Route Maintenance

An HELLO message is broadcasted by active nodes periodically after an HELLO_INTERVAL. In this way a node notigies its activeness. If there is a link failure, no HELLO are received in DELETE_PERIOD and a rout repair is tried. After a timeout, if the repair failed, a RERR is propagated to the source and destination nodes.

4 Power-Line Communications (PLC)

PLC is a pervasive, easy to install and cost effective communication method that uses electrical wiring to transmit at the same time both data and electric power. The data are sent though a low energy signal over the power wave, in this way it is possible to transmit data also in distribution networks.
By considering that the wiring of a powerline acts as an antenna and that this can cause interferences, different techniques are used to make them unshielded and untwisted. Moreover the 50 - 60 Hz electrical signals are transmitted at at least 3kHz to reduce the interferences.
The possible PLC applications are

- Telemetry
- Radio Broadcasting. Some radio programs are converted into lines
- Automotive. Digital data transmission over power lines inside the car to control the multimedia, instrumentation, climate, ...
- Home networking. This can be referred to the list mile access or to the devices inside the home. The main advantage of this application is to transform all the power outlets into broadband connections for devices. Moreover, if the data carries information about the power systems it is possible to detect illegal electricity usage and to monitor the power quality.

4.1 PLC categories

The PLC categories are mainly two:

- Narrowband. Used in house application for low bit rates HAN and outdoor automatic metering reading and remote surveillance and control. The bitrate is up to 800 kbps with 3-500 kHz of bandwidth. The transmission is periodic (once every 15 minutes today, in the future it will be once every minute) based on CSMA and Orthogonal Frequency Division Multiplexing (OFDM). Regarding the modem, it should consume less power than 30W (light bulb), whose largest consumption is in the power amplifier for the transmission. The coverage is up to few km with repeaters, on long power lines, the PLC signal is refreshed by filtering out the signal from the powerline, than it is demodulated and remodulated on a new carrier frequency. Finally it is re-injected onto the powerline.
- Broadband. It is used indoor for high speed HAN (up to 200 Mbps) and outdoor for providing broadband internet access. The frequencies are higher (1.8-250 MHz), even if the range is shorter (up to 1500 m). This category (BPL) is used to transit data over AC Medium Voltage distribution wiring between transformers and AC LV or transformers and customer outlet (240V). In this way the expensive network maintenance is avoided.

4.2 Noise in PLC

Regarding the Power Lines, those are affected by several sources of noise: Electric motors and sparking power-line hardware can incidentally interfere with the communications. The unintentional emitters are some types of microprocessors used by power-company which generate internal radio signal without the intention of transmit it. Finally there are intentional emitters, such as remote-reading meters.
In addition, the PLC is affected by non-Gaussian noise due to bulbs, lamps, switching power supplies, etc. All PLC is affected by the background noise, this is spectrally shaped and is due to the overlapping of low intensity noise sources.
The switching power supplies affect the Narrowband PLC with Cyclostationary Impulsive Noise, it can be synchronous or asynchronous to half AC cycle. This noise can be up to 40dB higher than thermal.
Finally random impulsive bursts micro-milliseconds long, called Asynchronous Impulsive Noise, affects the Broadband PLC.

4.3 HomePlug Powerline Alliance

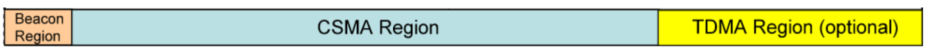
HomePlug is a standard series for PLC aiming at connecting devices in home, transmitting HDTV and VoIP in home and working with Smart Grids and IoT.

4.3.1 HomePlug 1.0

The standard has been designed to allows the devices connection in home. The physical layer is characterized by OFDM, which uses 84 equally spaced subcarriers (1-4.5 MHz) and uses turbo codes (FEC).
Regarding the MAC layer, it appends Ethernet frames with encryption and data management. The packets can be segmented and reassembled. The access is CSMA/CA with 4 different priority levels. The heavy loads are allowed thanks to the backoff algorithm.

4.3.2 HomePlug AV

It aims at providing HDTV and VoIP in home over existing AC wiring. This standard is interoperable with the HomePlug 1.0 and is robust even in high noise environment.
It operates at (2-28 MHz) with 200Mbps channel. The codes are the Turbo Convolutional ones (TCC) and the modulation is adaptive by varying from BPSK to 1024 QAM.
Regarding the MAC layer it is connection oriented and connection free, supporting TDMA and CSMA/AC. Also this standard has 4 priority levels for QoS and delay sensitive applications, since it has to deliver multimedia content. Similar to the ZigBee, it has a central coordinator (CCo) which communicate scheduling through beacons. The TDMA region, which is optional, is coordinated by CCo to ensure a certain QoS.



The Central Coordinator controls a logical network composed by AV nodes. It learns the topology by receiving the AV Discover Beacons sent periodically. These nodes have a list of networks and of other listened nodes. The CCo periodically asks the nodes their

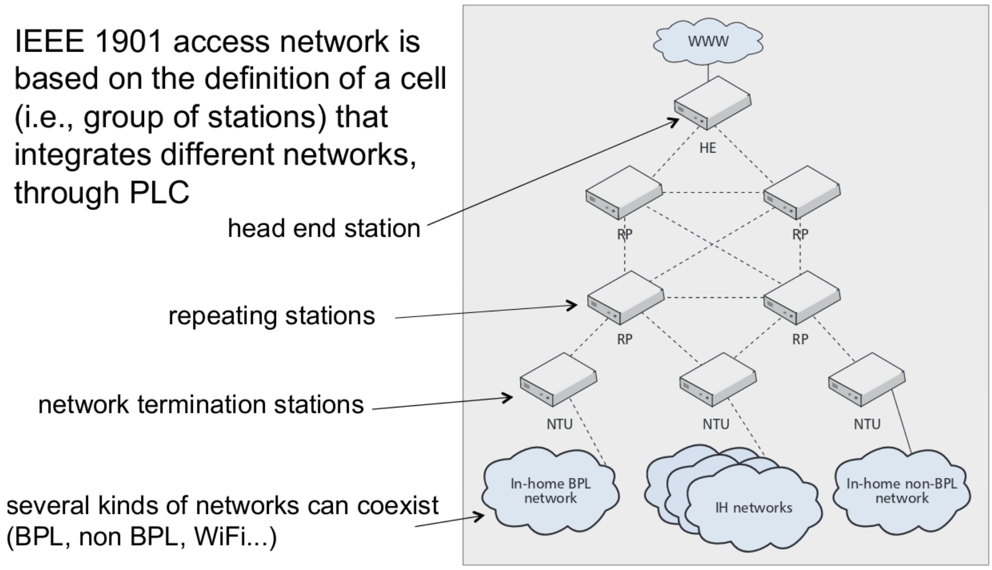
lists. The CCo roles is not permanent, since, by consulting a topology map, it evaluates if a node can be a better CCo.
When a new device is turned on, it listens to the medium. If a beacon is received, it tries to join, otherwise it becomes a new CCo.
Regarding the Channel Access Priorities, they goes from CAP3 (highest) to CAP0 (lowest). CAP3 and CAP2 can set two symbols of the Priority Resolution Slots (PRS0, PRS1). When these symbols are set to 1, CAP3 and CAP2 can transmit during the PRS.

4.3.3 HomePlug AV2

It is interoperable with HomePlug AV and HomePlug Green PHY 1.0 and, with respect to the AV it has an additional bandwidth (30-86 MHz) with the usage of over 60 carriers and the bitrate is up to Gbps at the physical layer and 500 Mbps of data. It is an ideal backbone for hybrid networks with Wi-Fi, since it supports of MIMO with beamforming (beamforming allows to direct and concentrate the wi-fi signal in a precise direction).

4.3.4 HomePlug Green PHY

It provides energy efficient and cost effective network for smart grid and smart energy management. Especially it is used for IoT and smart appliances, EV charghing, security monitoring, etc. It can be seen as the low-power adaptation of HomePlug AV.
The HomePlug Alliance cooperates with the ZigBee Alliance to develop the ZigBee/HomePlug Smart Energy Profile (SEP).
Regarding the MAC layer, it uses turbo codes as AV does and the supported data rates are 4, 5 and 10 Mbps. The subcarrier modulation is the QPSK one.
The OFDM is more robust thanks to the ROBO technique, which consists on sending multiple copies of data over different subcarriers. The data rate depends on the degree redundancy and the transmission does not require the knowledge of the channel conditions.
With respect to the AV, there is no TDMA for QoS guarantee.
The HomePlug Green PHY relies on IEEE 1901 which implements the powerline-based network. The access network is based on the definition of a CELL, or group of stations, which integrates different networks.



4.3.5 Power Save Mode

Different windows exists:

- Awake Window: the device Rx and Tx in this window and it lasts 1.5 ms - 2.1 s
- Sleep Window: the device cannot Rx and Tx
- Power Save Period: it is the sum of Awake and Sleep windows
- Power Save Schedule: it defines the power save period and awake windows. The awake one of different devices should overlap as much as possible to maximize the communication and it is coordinated by the CCo

5 Power over Ethernet

PoE is a mechanism for supplying power to network devices over the same cabling used to carry network traffic. Powered Devices can be IP telephones, wireless LAN AP and network cameras.
This technology delivers DC power over data and this feature can simplify the network installation and maintenance by using the switch as a central power source.
The main advantages of PoE is that a single cable between switch and device is required, in this way the device installation is easier, space saving and safer, since no mains voltages are required. The failures are avoided thanks to a UPS and the devices can be shut down or rest remotely.
If PoE is used, up to 15W can be delivered over two of the four twisted pairs. In PoE+ 30W can be delivered. However, by using all the 4 twisted pairs, up to 60W. The maximum distance from the switch is 100 m.
In PoE, the Power Source Equipment (PSE) automatically determines if a connected device is powered or not and auto-detect its power class. The configuration phases are 3:

- Detection, it is ¡ 500 ms and the PSE determines if the device is a one which can use PoE or not. This is performed by applying a DC voltage between the PSE and the Device and by measuring the received current. This is performed at regular intervals. The minimum backoff time is 2 s.
- Physical Layer Classification. In this phase the PSE determines how much power is required. This phase lasts from 50 ms to 75 ms. The power classes is determined by analyzing the received power level.
- Power-on. In this phase, after a 15 us of start-up period, the device is operative. When the device is disconnected, the switch senses a received power decrease. If this lasts from 300 ms to 400 ms, the device is considered disconnected and no more power is given to it.

Even if the PoE is robust and power saving, however big switches might consume considerable amount of power (e.g. 1500 W). For this reason additional cooling might be needed.

6 IEC 61850

IEC 61850 is a standard for designing the intelligent electronic devices at electrical substations to perform Smart Grids automation. The modern substation automation is structured in three basic levels:

- Stetion level: provides overview across the whole station, it is placed in a control room. It includes HMI workstations, backup computers and GPS receiver.
  Its tasks are data analysis from the bay levels and the submission of control commands.

- Bay level: it is performed the maintenance in only one bay, or set of devices managing some functions. It includes protection for the devices, transformers, generators and circuit breakers.
  In this level, the bay data are collected and actions on the power circuit are performed.

- Process level: interface between the automation system and the switch-gear. It includes remote I/O, actuators, sensors and meters.
  This level gets performance data and perform the control commands submitted by the station level.

The communication among different levels is vertical and it is performed with high speed Ethernet, whereas across one layer the communication is horizontal.
The IEC 61580 relies over the TCP/IP and Ethernet networks. It provides the interoperability between the substations of different energy companies. It is scalable and works with heterogeneous existing systems.
The standard defines naming convention to provide the self description and discovery of the Intelligent Electronic Devices (IED) and defines data format and structures to perform an easy substation management.
Moreover, to make applications and database independent on communication protocols, the Abstract Communication Service Interface (ACSI) is used. This standard defines a set of abstract services to access and manipulate data objects and defines their behavior.
Another feature of the IEC is the Substation Configuration description Language (SCL) which standardizes the topology description of the substation.

6.1 Devices

The managed devices are divided into physical ones and logical ones organized in logical nodes. Thanks to this logical device concept, a single physical device can act as a gateway for different devices and different kinds of information. The logical nodes contained in a logical device are parts of a function and they are defined by data objects. These objects are modeled by Common Data Classes (e.g. postion, properties, activity status, control data, etc.).
Regarding the naming, the IEC provides an intuitive system to make operation and management easier. The first letter of the logical node indicates its type (e.g. P stands for protection, so PDIF stands for Differential Protection). The name structure is the

following:

$$\text{IED1/XCBR\$POS\$sty} \tag{1}$$

which can be summed up as:

$$\text{logical\_dev/logical\_node\$data\_obj\$data} \tag{2}$$

6.2 Substation Network

The IEDs communicate with the Gatway through the substation bus at 100 Mbps over Ethernet. They can communicate also with the Merge Units, which collects data from sensors and digitalize them, through the process bus at 10 Gbps over Ethernet too.
The control model is the GOOSE, which allows to use multicast or broadcast services to make multiple physical devices have the same data. The data grouped into a dataset can be transmitted in t $\leq$ 4 ms.

6.2.1 GSE and GOOSE

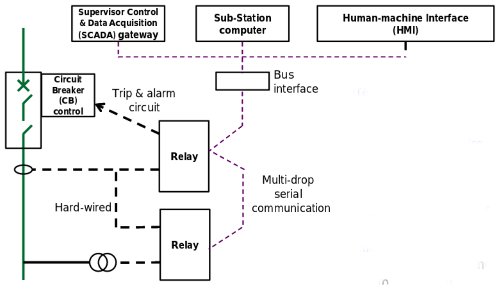
GSE stands for Generic Substation Event, which is a fast and reliable control model to indicate events inside the substation (e.g. alarm, state change, etc.) by exploiting the publisher/subscriber paradigm. There are two modes, the Generic Object Oriented Substation Event (GOOSE) and the Generic Substation State Event (GSSE). This last one is limited to information about state changes within a lists of bits, or bit maps. The delivery time is longer than the GOOSE, but the message is simpler thanks to the bit maps.
The GOOSE allows the communication directly at the data link layer and it ensures that the same event is received by multiple physical layer, sometimes by retransmitting the data. With respect to the GSSE, diagnostic functions can be included in the data set.
Thanks to the publisher/subscriber paradigm, the sender publishes a GOOSE message. This is received only by the subscriber devices and the reaction of each receiver depends on its configuration.
An example of the GOOSE usage is the Tripping. It consists of using a circuit breaker to open the circuit in the event of a thermal overload, short circuit or ground fault. When a failure is detected from the device A, it publishes a GOOSE message in multicast. The device B receives the message but, according to its functionality, does not react, whereas the device C receives it and turn off the circuit breaker.

6.3 Substation Configuration Language (SCL)

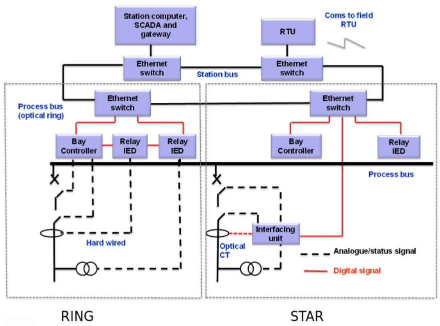
It is used to describe the substation topology by exploiting the XML. The main advantage of the SCL is the interoperability among IEDs using different protocol and the unique configuration of the substation. Moreover, thanks to the portabilty (each IED has a SCL file which defines its configuration), the SCL is the basis for the success of Plug & Play.
The main challenges of the SCL is the ability of change specifications during design phases with the aid of the proprietary configuration tools for multiple vendors. The main con of SCL are the security vulnerabilities due to incorrect system configuration.

7 Automation of Distribution Electricity Systems

Automation of distribution systems is increasing to improve the quality of supply and integrate more distributed generations. The automation has seen a paradigm shift: traditionally, circuit-breakers were connected to relays with current and voltage transformers through wires. The remote interrogation to monitor the system was performed by station computers thanks to *multi-drop bus*. This means that all the component were connected to the electrical circuit and when one device was sending information, all the others were listening.



According to what has been said, modern distribution systems are divided into three levels: the station one, including the substation computer, the HMI and the gateway; the bay level including the controllers and the intelligent electronic devices and the process level, including switchgear control and monitoring, transformers and sensors.



There are two kinds of connection:

- Ring connections: hard-wired links are used to transmit analogue signals and current/voltage measurements to the bay controller and IEDs
- Star connections: Both analogue and digital signals are sent to the interfacing unit before being transmitted to the bay controller and the IEDs

In both of the connections the process bus transfers data to the station bus. It is in LAN form connecting several Ethernet switches through a fiber-optic circuit. The station computer retrieving data from the station bus has the SCADA (Supervisory Control And Data Acquisition) software to process collected data. Thanks to the Ethernet-base data exchange and the IEC 61850 communication protocol, modern distribution automation systems allows a low cost and flexible service with respect to the traditional ones which required kilometers of hard wires.

7.1 Distribution Management Systems (DMS)

A DMS is a collection of application to monitor, control and optimize the performance of the distribution system and manage it. Basically it acts as a decision support system to assist the control room. It is required since the manual traditional procedures in critical events are not sufficient or efficient.
Its main goals are the system monitoring to provide the continuity of supply, management purposes such as plant records, inventory control and mapping (GIS), short-term planning and optimal network expansion by reducing the costs.
In the DMS structure, applications need modelling and analysis tools, whose inputs are network status, network parameters and customer information. These data are provided by SCADA and Customer Information System (CIS).

7.1.1 SCADA

SCADA is a control system architecture enabling monitoring and the process supervisory management at high-level by providing a simple GUI. The control system is both manual (circuit breakers are manually controlled by operators) and automatic (triggered by events or times).
When the switchgear changes its status or circuit limits are violated, the Remote Terminal Unit (RTU) automatically passes this information to the control center in near-real-time. The SCADA monitoring function generates an event by comparing measured data and limits. The event is processed and classified by the SCADA event processing function. Relative information are sent to the system operators via HMI.
Regarding the data storage, real-time measurements are stored in the real-time database. They are periodically collected and old values are overwritten by new updates.

7.1.2 CIS

Customer Information System provides all the useful information and tools for customers such as managing the complaint, the payments and the bill, holding the inventory meters and locations or providing info to customers affected by outages.

8 Smart Grids Architecture Model

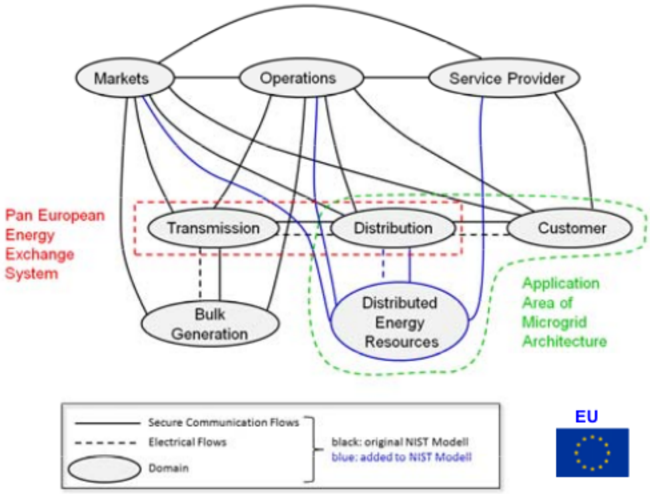
The reference model of smart grids is a set of diagrams and descriptions useful to describe, discuss and develop the architecture without representing a specific implementation. Since actually the standards and protocols set is not completed, NIST developed a three-phase plan:

1. Accelerate the identification and consensus on Smart Grid standards

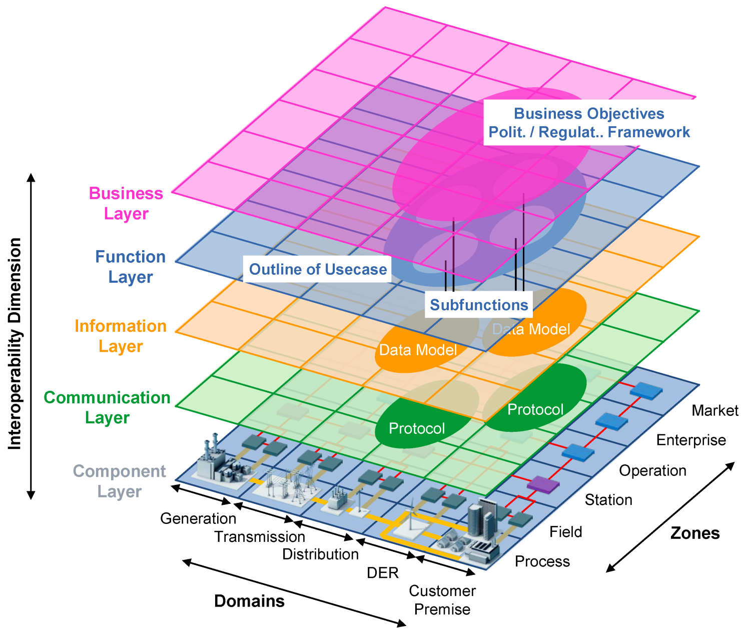
2. Establish a robust Smart Grid Interoperability Panel, which supports the development of the additional needed standards

3. Create a conformity testing and certification infrastructure.

To integrate the Distributed Energy Resources (DER), which are small-scale units of local generation connected to the grid at distribution level (typically 3kW - 10MW), the NIST model has been edited. The main task is to separate the existing domains from the new DER one:



It is possible to define the SGAM as a framework offering support for the design of smart grids causes though an architectural approach, so in can be used for both current implementation and future implementations of the smart grid. It can be considered as a 3D model merging the dimension of 5 interoperability layers, with two dimensions of the Smart Grids Plane zones, or hierarchical levels of power system management, and domains of the complete electrical energy conversion chain:



8.1 Hierarchical Zones

1. Process. It includes the physical, chemical or spatial energy transformations and the physical equipment (generators, transformers, etc.)

2. Field. It includes protection, control and monitoring equipment to check the process of the power system (protection relays and intelligent electronic devices to collect data)

3. Station. It represents the aggregation level which performs data concentration (plant supervision and Data collectors)

4. Operation. It hosts the power system control operation such as SCADA, Distribution Management Systems (DMS), Energy Management Systems (EMS) or virtual power plant aggregating several DER

5. Enterprise. It includes commercial processes, services and infrastructures (e.g. staff training, customer relation management, billing, etc.)

6. Market. It is referred to market operations such as energy trading.

8.2 Domains

1. Generation. It represents the generation of electrical energy in several forms (fossil, nuclear, hydro, solar, etc.)

2. Transmission. It represents the infrastructure which transport the electricity over long distances

3. Distribution. It represents the infrastructure which distributes electricity to customers

4. DER

5. Customer Premises. It hosts end users and producers including industrial, commercial and residential facilities.

8.3 Interoperability Layers

1. Component Layer. It regards the physical distribution of all smart grids entities (applications, equipment, communication network and infrastructures, etc.)

2. Communication Layer. It describes protocols and mechanisms for the information exchange. For each communication it is described the use case, functions, services and data models

3. Information Layer. It describes the information used and exchanged and contains the canonical data models.

4. Function Layers. It describes functions and services by underlying their relationship from an architectural point of view. They are independent from physical implementations.

5. Business Layer. It supports business executives in decision making, new business model and specific business projects.

SGAM is useful to compare different architecture and coordinate work between different technical committees and stakeholders. Moreover it is possible to map use cases and customers/competitors. Another use of SGAM is the analysis of the standards and installed architectures, together with the development of migration scenarios.

8.4 Use Case: Mapping Process to SGAM

Let's consider the Control Reactive Power of DER Unit case study.The objective is to monitor and control voltage level of distribution grids in tolerated limits, after having checked that all the required information is provided.

Actors: grid, DER, Distribution IED, Distribution data collector, DMS, Distribution stabilize and optimize, Network operations and reporting/statistics.
Functions: Data acquisition, SCADA, Volt control, DER control and Audit. The first step is to map the actors and functions to the Smart Grid Plane. To have an overview of the process, the DER controller is linked to the SCADA system. The generated units are put into the grides. The IED measures the amount of generated energy and send data to the distribution center, linked to the SCADA too. Here, the DMS perform the Volt control together with the distribution stabilizer and optimizer and finally, statistics are taken from SCADA and provided to the enterprise users.

1. Component Layer

   (a) Process zone. Physical grid on the Distribution domain and DER on the DER domain

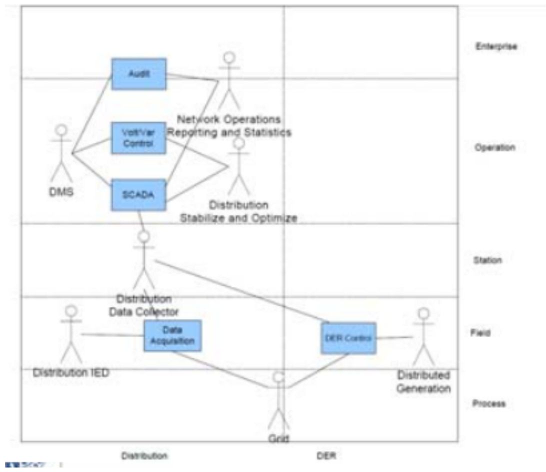
   (b) Field zone. IED on the Distribution domain and DER controller on the DER domain.

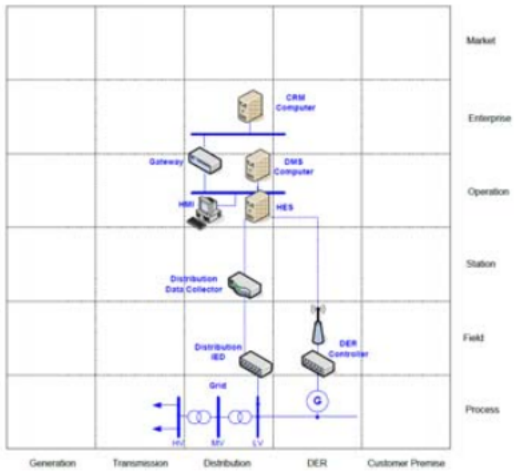
   (c) Station zone. Data collector on the Distribution domain.

   (d) Operation zone. DMS Computer and gateway

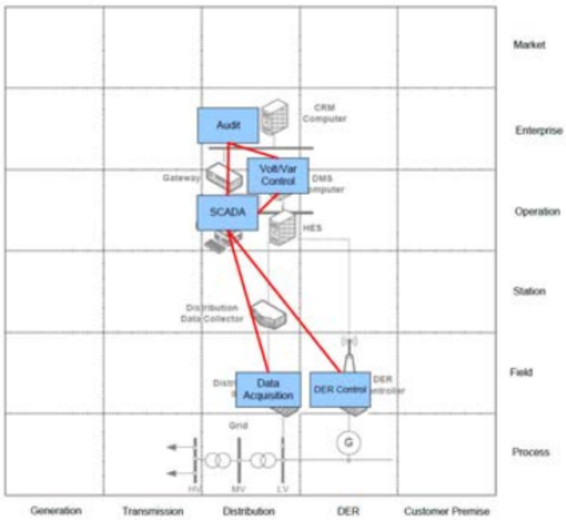
   (e) Enterprise zone. Customer Relastionship Management computer (CRM)

   (f) Market zone. None.

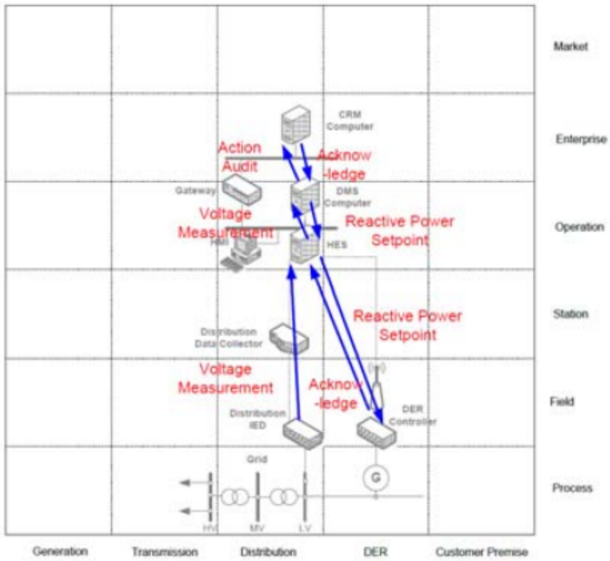




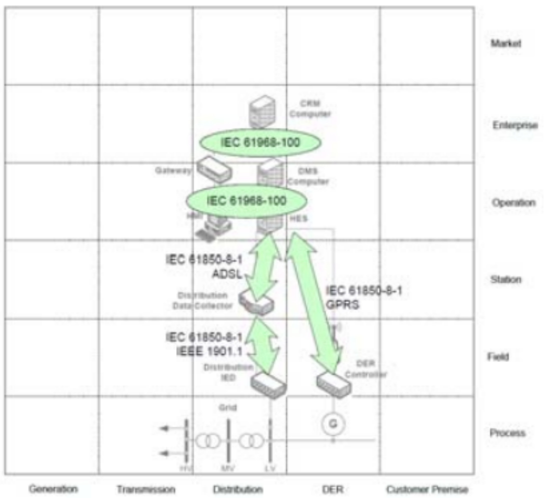
2. Function Layer
   (a) Field zone. Data acquisition on Distribution domain, DER control on DER domain.
   (b) Operation zone. SCADA and Volt control.
   (c) Enterprise zone. Audit function.



3. Information Layer. With labelled arrows it is possible to define which information is exchanged between functions and components. E.g. from IED to SCADA the voltage measurement is performed



4. Communication Layer. In this layer the protocols are reported between the actors. In the Enterprise and Operation zone, the IEC 61980-100 is used, whereas in the Field zone the IEC 64850 is used.



9 Demand Side Management

Demand Side Management (DSM) consists in mechanisms that aim at modifying the consumer's demand profile, in time and/or shape, to make it match the supply. In this way it is possible to incorporate renewable energy resources by facilitating the integration of distributed generation. Moreover emergency situations are handling easier.

For different sectors, different solutions are designed in terms DSM. The producer develops the profile according to the application field. In different businesses (with the same order of maginitude) the potential savings are similar in % of total consumption (around the 18% of savings).

9.1 Demand Response

Demand Response (DR) is a class of DSM mechanisms and consists in rescheduling the users' energy usage patterns in response to the variance of the power utility's incentive or electricity price. So basically it is designed to reduce the demand at peak time periods and to reduces the operating expense from expensive generators. In this way the consumer is involved in the loop and it is aware of the energy issues. Moreover it can changes its profile to fit the trend.

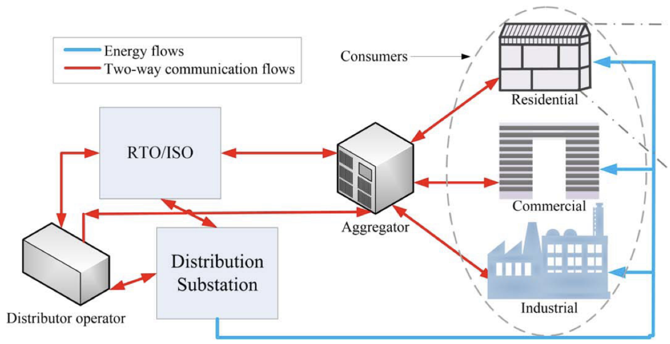
The Demand and Response concept is needed to reach significant objectives such as making a power system more reliable and leading to mutual financial benefits for both the power utility and all users. If we consider this system in a long term application, we would have a reduction in generating emissions and so alleviate the environmental impacts, by enabling a more efficient utilization of current grid capacity. Having a power distribution system based on demand and response will reduce the total consumption and so the need for large power generation systems, needed to meet peak demand. Reducing overloads in distribution systems and prevent emergency conditions will also occur in a setting of DR.

9.2 Participants and Operation

In the setting of DR, the main participants are:

- Distributor System Operator that controls the distribution system (DSO)
- Independent System Operator or Regional Transmission Operator (RTO/ISO) that defines the preferred demand volume and time duration
- Consumers.

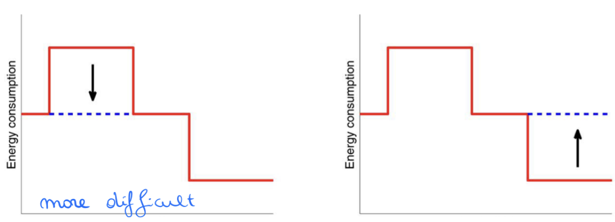
Consumers and DSO/ISO are linked by an aggregator:



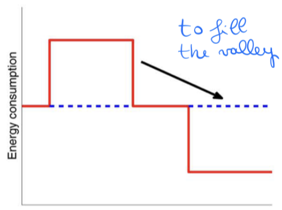
The RTO/ISO defines the preferred demand volume and time duration and the DR aggregator performs the selection of the participants based on their availability to the proposed DR, computes the total demand and then reports it to the RTO/ISO and, possibly, reports also the total demand to the DSO that can proceed with system optimization.

Since the load has to change according to the power demand, several load changing profile exists. Three of them are:

- Peak clipping: reduces peak consumption, avoiding that the load exceeds capacity of substations, or thermal limit of feeders and transformers. This profile-change is more difficult to apply;
- Valley Filling: promotes the off-peak energy consumption by using energy storage devices
- Load Shifting: shift the energy consumption from on-peak to off-peak time periods (peak clipping + valley filling)



(a) Peak Clipping and Valley filling



(b) Load shifting

9.3 Loads and Approaches

Loads are portion of circuits that that consumes (active) electric power. This is opposed to a power source, such as a battery or generator, which produces power. In electric power circuits examples of loads are appliances and lights. Typically, the loads are quite unbalanced since residential one has peaks in the afternoon, industrial ones instead in the morning. We use the **Peak Average Ratio (PAR)** as an indicator: $\frac{Peakdailyload}{Averagedailyload}$. Loads are subject to many different factor, such as the day, the period of the year and location.

To better manage the loads, there are two approaches:

- **Incentive-based approaches**: Reward (with credits or discounts) consumers for changing their load profile in periods of system stress; often associated to penalization to consumers that do not adapt. The reduction of the consumption is possible with:
  - *Direct load control*: the utility has remote control of some appliances, and control them according to the system needs (usually water heaters, air conditioning);
  - *Interruptible load*: when needed, the consumers are requested to cut their load to predefined levels; consumers who accept receive some discount on the bill, penalization is applied to those who do not accept;
  - *Emergency reduction*: under emergency, and aiming at system reliability, consumers receive incentives for load reduction.
- **Price-based approaches**: Set different electricity prices at different times, and users dynamically adapt their load profile to price: it is based on the user's interest to reduce its cost

- *Pricing* is set based on the cost of electricity;
- *Time of use pricing*: pricing is set on relatively large intervals (typically larger than 1h); prices are set in advance and kept stable for long
- *Critical peak pricing*: in addition to setting like in the *time of use pricing*, in some critical situations, peak price is increased to reduce consumption. Price is some intervals might vary (typically the peak price) based on a number of possible settings. In some cases, even the duration of the critical period might vary;
- *Real time pricing*: over quite short periods (1h, 15 min), pricing is released short in advance, a time-slot ahead or the day before. They increase effectiveness of DR by exploiting better the willingness of consumers to participate to the DR program, there's the need of reliable two-way communications and reliable smart meters.

Price-based is more suited for residential consumers, incentive based to industrial ones (commercial consumers are somehow in between). The difference is due to the capacity of dynamically and quickly change the load, that is higher for residential with respect to industrial consumers

9.4 DR Programs

To realize efficient DR programs it is necessary to distinguish between the different types of users:

1. **Residential consumers**: they have an unpredictable behavior, they act on energy efficiency of their house appliances and in load shifts for their consumptions. As we could expect, since the behavior is quite unpredictable, the loads patterns are different. Typical patters are:
    - short range consumers, who are only concerned about the power price at the current time instant
    - real-world advancing customers, with consumer perception in current and past periods only
    - real world-postponing consumers, whose perception depends on current and future prices only
    - real-world mixed consumers, who are a mixture of postponing and advancing customers
    - long range consumers, who are able to shift their consumption over a wide range of time
2. **Commercial consumers**: they typically act on the building and its infrastructure (heating, lighting, cooling, etc.) and they respond to DR request by acting on the building energy consumption;
3. **Industrial consumers**: often, DR is designed for reliability of the energy infrastructure.

Often DR programs are formulated as optimization problems with various possible optimization objectives:

- Minimize electricity cost. We can achieve this by maximizing the use of renewables and the economic benefit of utility; by minimizing the electricity generation cost and the peak demand.
- Minimize aggregate power consumption (at peak) by maximizing the load shifting.
- Jointly minimize electricity cost and aggregate power consumption
- Maximizing the social welfare while minimizing aggregate power consumption.

Controlling mechanisms can be of 2 types, the first one is a **Centralized** one where decisions on a load activation/scheduling are taken by a centralized controller (the power utility or aggregator). The second type of control mechanism is a **Distributed** one where the utility sends price to the consumers that coordinate to reduce the load.

9.4.1 Task Scheduling

In order to reduce the load we have also the scheduling of tasks that have different characteristics:

- "Must-run-tasks" do not tolerate delays, such as lights or fridges. By considering T_a as the set of timeslots in which the appliance has to be powered, given the characteristics of the appliance, the power demand $x_a(t)$ of the appliance in time slot t is:
$$x_a(t) = \begin{cases} b(t) & t \in T \\ 0 & \text{otherwise} \end{cases}$$
- Schedulable: Shiftale appliances. They can be stopped or adjusted. The only concern is the completion time. By defining a target deadline for the task to be completed, D_a with total demand e_a, the power demand $x_a(t)$ of the appliance in time slot t is:
$$x_a(t) = \begin{cases} 0 \leq b(t) \leq x_a^* & t \leq D_a \\ 0 & \text{otherwise} \end{cases}$$
$$\text{with } \sum_{t=0}^{D_a} x_a(t) = e_a$$
where x_a^* is the maximum power demand.
- Shedulable: Shiftable w/o interruptions. Once started, the task should be completed without interruptions. By defining e_a as the total demand and $r_a(t)$ as the remaining demand at time t, given starting time T, the power demand $x_a(t)$ of the appliance in time slot t and the remaining demand $r_a(t)$ are:
$$r_a(t) = \begin{cases} e_a & t < T \\ e_a - \sum_{\tau=r}^{t} x_a(\tau) & t \geq T \end{cases} \quad x_a(t) = \begin{cases} 0 \leq b(t) \leq x_a^* & t \geq T \\ 0 & \text{otherwise} \end{cases}$$
where x_a^* is the maximum power demand.

9.5 Issues and Challenges

The key to DR is the willingness to participate (according to some studies, consumers are little willing to cooperate). It is difficult to tune the mechanisms and achieve a desired overall benefit from a DR program. The benefit is sometimes unevenly distributed among consumers: those who consume little, cannot really reduce consumption and are penalized, those who participate pay more during peak hour, and, hence, they end up paying more than those who do not participate. So we see that users have several different attitudes and, correspondingly, several DR programs should be proposed. The way in which feedbacks about prices, consumptions, grid stress are proposed to users can be quite important in making them react properly. Now let's see what are the main challenges in the approach of Demand and Response. The need of DR program will increase with the increase of the penetration of renewable sources that are intermittent, difficult to predict (need for good forecasting models), make energy production more variable. In presence of multi-sellers/multi-buyers scenarios, price setting are complex and global optimization are difficult to achieve. Smart metering and communication infrastructures have to guarantee the support.

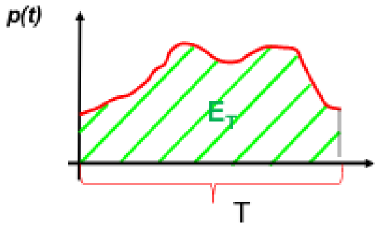
9.6 Communications for Demand and Response

Communications need to relay on 3 main components:

- **Interoperability**:it is fundamental for data exchange among the different components of the smart grid, it requires the definition and adoption of open standards and layered architectures are needed to guarantee flexibility and the possibility to change some of its components;
- **Scalability and flexibility**: DR is particularly effective when a large no. of consumers participate (more possibilities to adjust loads),Communication infrastructure should also be scalable and Redundancy and alternative paths/routes;
- **Security**: Data integrity, confidentiality, authentication. Malware and malicious behaviors can compromise effectiveness of DR mechanisms, implying cost increase and possible grid damages.

A Mathematics

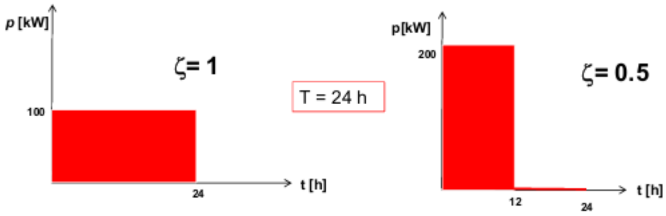
By defining the time-changing power *p(t)*, the energy can be defined as the integral of the power over time: $E_T = \int_0^T p(t)dt$



The limited possibility of storage in electricity systems is conditioned by the load factor, or the average load divided by the peak load in a specified time period

$$\zeta = \frac{p^A}{p^{MAX}} = \frac{\frac{1}{T}\int_0^T p(t)dt}{max|p(t)|} \tag{3}$$

This means that if one user A needs 100kWh for 24h and one user B needs 200kWh for 10h, the investment of B is greater the A's one, even if from the customer point of view, the draw of energy is the same (since $E_T \cdot t = 240kWh$ in both cases.



The load factor can be considered also as the *utilization hours*, which is the ration between the electricity consumed and the maximum power withdrew discretized in 15' in the relevant period T of h_T hours. It can be expressed as the number of hours for which the load should withdraw the maximum power to withdraw the entire electricity wthdrawn in the relevant period.

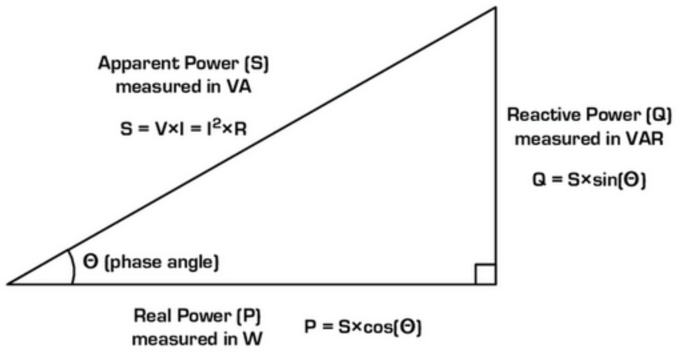
$$\zeta = \frac{E_T}{P^{MAX}}\frac{1}{h_T} = \frac{h_U}{h_T} \tag{4}$$

The utilization hours provide an idea of the behavior of the client.

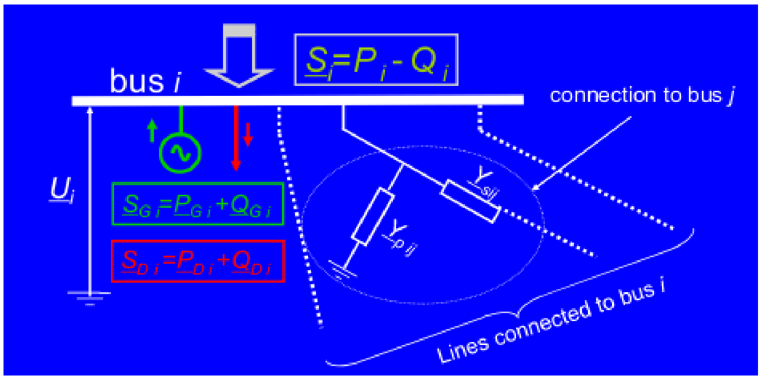
A.1 AC Power Flow Equation

The power system is modeled by generator and load buses connected by lines and transformers. The Power Flow Equations represent the constraints that the power system needs to satisfy under normal operation and reflect the relationship between the power (real and reactive) and the voltage (amplitude and phase angle).
The real, or active, power is the actual power which is dissipated in the circuit. The reactive power is the useless power which only flows between the source and load.

The considered system is a three-phase balanced one with the equivalent one-phase circuit. The purpose is to determine the voltage at each bus for a given configuration of generators and loads. The hint is to determine the line currents at each bus and then the power flows (real and reactive). The needed relationship is:



Now, for the bus i:



Where

- S_{Di} is the complex power withdrawn by the load at bus i
- S_{Gi} is the complex power injected by the generator at bus i
- S_i is the net injected power at bus i.
  - P_i is the net real power injected
  - Q_i is the net reactive power injected

Fundamental relations where **X** or **x** is a vector and $\underline{x}$ is a complex number:

$$Ke^{ix} = Kcos(x) + jKsin(x) \tag{5}$$

$$\underline{U} = Ue^{j\delta_U} \tag{6}$$

$$\underline{I} = Ie^{j\delta_I} \tag{7}$$

$$\underline{S} = P + jQ = \underline{U}\underline{I}^* = UIe^{j(\delta_U - \delta_I)} = UI[cos(\delta_U - \delta_I) + jsin(\delta_U - \delta I)] \tag{8}$$

$$\underline{y}_{i,k} = y_{i,k}e^{j\gamma_{i,k}} \tag{9}$$

$$P = Re\{\underline{S}\} \tag{10}$$

$$Q = Im\{\underline{S}\} \tag{11}$$

$$\underline{\mathbf{I}} = \underline{Y}\,\underline{U} \tag{12}$$

$\underline{Y}$ is the admittance matrix. The element $\underline{y_{ii}}$ on the diagonal are the indcidenting admittances to the bus, $\underline{y_{ij}}$ is minus the admittance between bus i and bus j.

$$if\ X_{i,k} = j.2\ \ then\ \ Y_{i,k} = \frac{1}{jX_{i,k}} = -j5 \tag{13}$$

Finally:

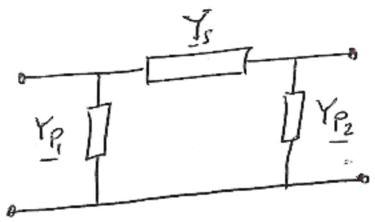
$$\underline{S_i^*} = \underline{U_i^*} \sum_{k=1}^{n} \underline{y_{ik}}\,\underline{U_k} \tag{14}$$

$$P_i = \sum_{k=1}^{n} y_{ik} U_i U_k cos(\delta_k - \delta_u + \gamma_{ik}) \tag{15}$$

$$Q_i = -\sum_{k=1}^{n} y_{ik} U_i U_k sin(\delta_k - \delta_u + \gamma_{ik}) \tag{16}$$

A.2 Transmission Lines

A transmission line can be modeled as:



Possible formulas are:

$$X_s = R_s + jX_s \tag{17}$$

$$Y_s = \frac{1}{R_i + jX_i} \tag{18}$$

$$Y_{p1} = Y_{p2} = j\frac{B_p}{2} \tag{19}$$

The admittance matrix is:

$$\begin{bmatrix} \sum_{i=1}^{N} Y_{s,1i}\ -\ \sum_{i=1}^{N} Y_{p,1i} & -Y_{s,12} & -Y_{s,1N} \\ -Y_{s,12} & \ddots & -Y_{s,2N} \\ -Y_{s,1N} & -Y_{s,2N} & \sum_{i=1}^{N} Y_{s,Ni}\ -\ \sum_{i=1}^{N} Y_{p,Ni} \end{bmatrix} \tag{20}$$

A.3 DC Power Flow

Transmission matrix $\mathbf{H} \in \mathbb{R}^{LxN}$ where L is the number of lines and N is the number of nodes:

$$h_{(i,j),i} = \frac{1}{x_{i,j}} \tag{21}$$

$$h_{(i,j),j} = -\frac{1}{x_{i,j}} \tag{22}$$

$$h_{(i,j),k} = 0 \tag{23}$$

where $k \neq [i, j]$
Admittance matrix $\mathbf{B} \in \mathbb{R}^{NxN}$ where N is the number of nodes:

$$b_{i,j} = -\frac{1}{x_{i,j}} \tag{24}$$

$$b_{i,i} = \sum_{j=1}^{N} \frac{1}{x_{i,j}} + \sum_{j=1}^{N} \frac{1}{x_{j,i}} \tag{25}$$

$$\mathbf{A} = \mathbf{H}\mathbf{B}^{-1} \tag{26}$$

By calling $\mathbf{p}$ the array of the injected power in P.U., the vector of the powerflows of all lines is:

$$\mathbf{f} = \mathbf{A}\mathbf{p}^{'} \tag{27}$$

where a power in P.U. is $\frac{Power}{basequantity}$. (e.g. for 500MW and 150MW the base quantity is 100MVA, so 5 P.U. and 1.5 P.U.). If the sources or the sinks changes:

$$\mathbf{\Delta f} = \mathbf{A}\mathbf{\Delta p}^{'} \tag{28}$$

and the new powerflows are: $\mathrm{f}_{new} = \mathbf{f_{old}} + \mathbf{\Delta f}$ or, alternatively:

$$\mathbf{f_{new}} = \mathbf{A}\mathbf{\Delta p}^{'} \tag{29}$$

The result is the same.

B Load Shift

Work always in P.U.

$$\Delta V = V_A - V_B = ZI \tag{30}$$

$$|x| = \sqrt{Rex^2 + Imx^2} \tag{31}$$

$$\angle x = arctan(\frac{Imx}{Rex}) \tag{32}$$

Power on line:

$$P = \sqrt{3}VI \tag{33}$$

Power on bus:

$$P = VI \tag{34}$$

Loss on line:

$$L_{oss} = RI^2 \tag{35}$$

By considering different power values P_i obtained in different time slots $t_i = [t_1, t_2]$, the load factor ζ is:

$$\zeta = \frac{\frac{1}{T}\sum_{i=1}^{N} P_i(t_2 - t_1)}{P_{max}} \tag{36}$$

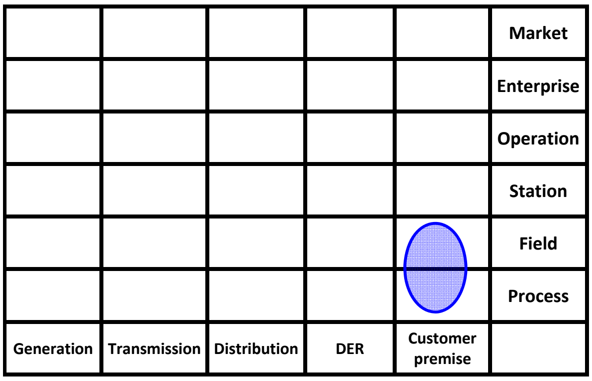
where T is the total period (e.g. $T = 24$ for hourly values related to one day).

C Sub-Networks

SMART GRIDS COMMUNICATION SUB-NETWORKS

- Subscriber Access Network

Network which is not part of the utility infrastructure, but involve devices and systems interacting significantly with the utility, like responsive loads in residences and commercial/industrial facilities, etc.



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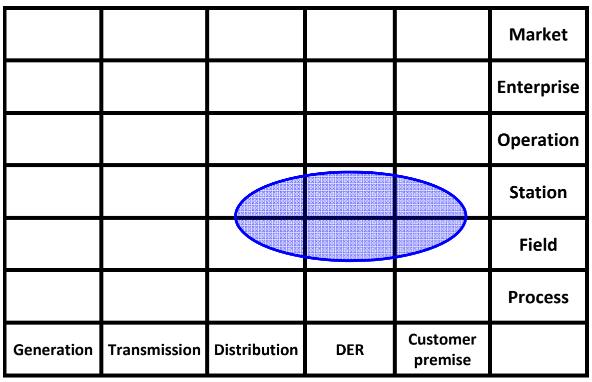
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Neighborhood network

Network at the distribution level between distribution substations and end users. These networks may serve metering, distribution automation, and public infrastructure for electric vehicle charging, for example.



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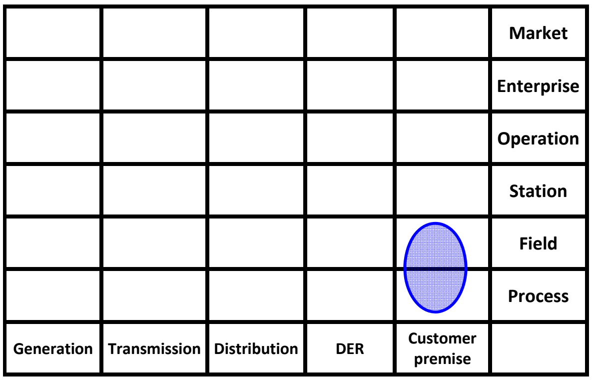

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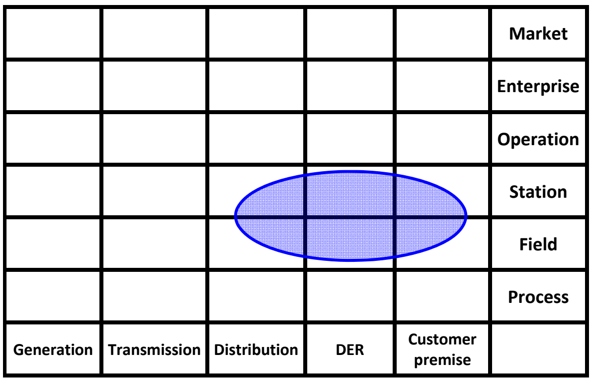

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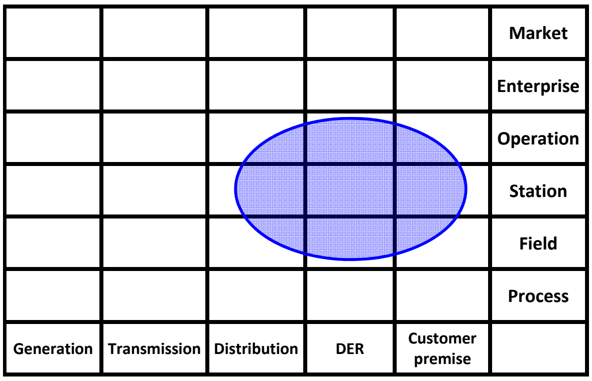
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Field Area Network

Network at the distribution level upper tier, which provides backhaul connectivity in 2 ways: directly back to control centers via WAN or directly to primary substations to facilitate substation level distributed intelligence.

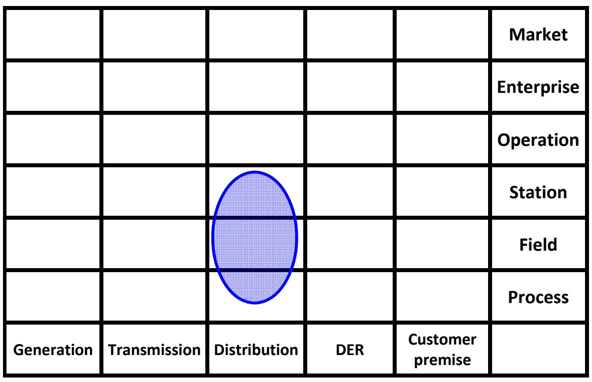


POLITECNICO DI TORINO

SMART GRIDS COMMUNICATION SUB-NETWORKS

- Low-end intra-substation network

Network inside secondary substations or MV/LV transformer station. It usually connects RTUs, circuit breakers and different power quality sensors.



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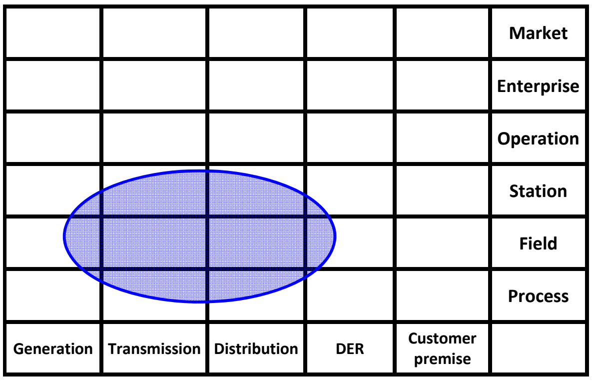
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Intra-substation network

Network inside a primary distribution substation or inside a transmission substation. It is involved in low latency critical functions such as tele-protection.



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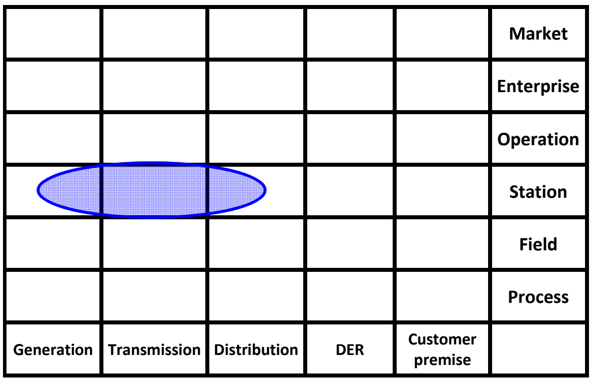
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Inter substation network

Network that interconnects substations with each other and with control centers. These networks are wide area networks with accurate latency and prompt response.

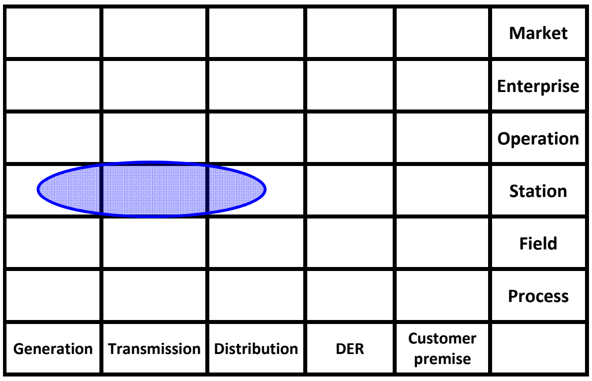


POLITECNICO DI TORINO

SMART GRIDS COMMUNICATION SUB-NETWORKS

- Inter substation network

It provides networking for SCADA, event messaging, and remote asset monitoring, as well as peer-to-peer connectivity for tele-protection and substation-level distributed intelligence.



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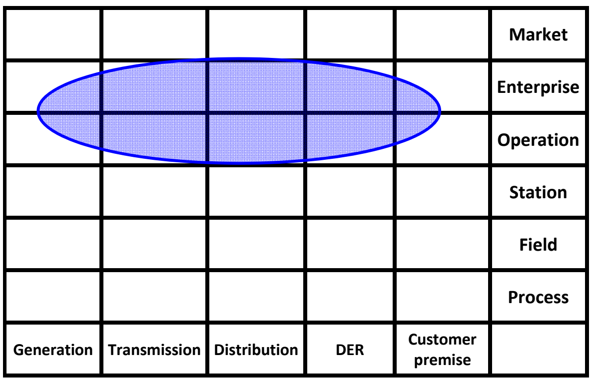
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Intra-Control Centre / Intra-Data Centre network

Networks inside utility data centers and utility control centers. They are not the same networks, as control centers have very different requirements for connection to real time systems, as enterprise data centers do not connect to real time systems for security.



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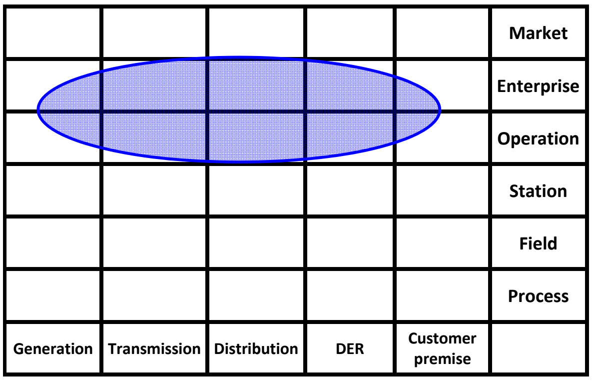
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Enterprise Network

Enterprise or campus network coverage is similar to the inter-control center network. Utilities typically have multiple control centers and multiple campuses that are widely separated geographically.



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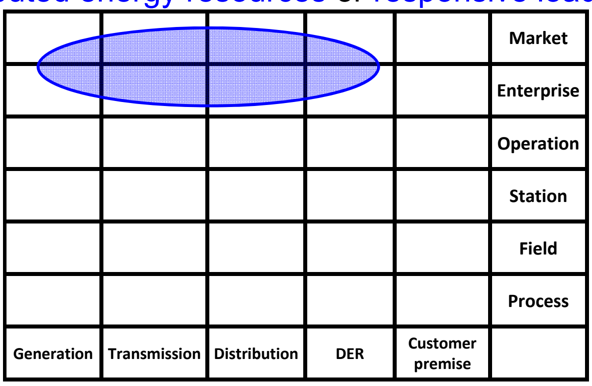
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Balancing Network

It interconnects generation operators and independent power producers with balancing authorities; It also interconnects balancing authorities with each other.
In some emerging cases, balancing authorities may also dispatch retail level distributed energy resources or responsive load.



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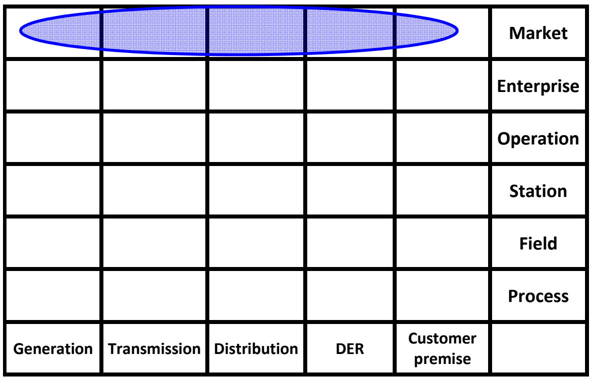
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Interchange network

Interconnecting regional reliability coordinators with operators such as transmission operators and power producers;

Interconnecting wholesale electricity markets to market operators, providers, retailers, and traders.

In some cases, the bulk markets are being opened up to small consumers, so that they have a retail-like aspect that impacts networking for the involved entities.



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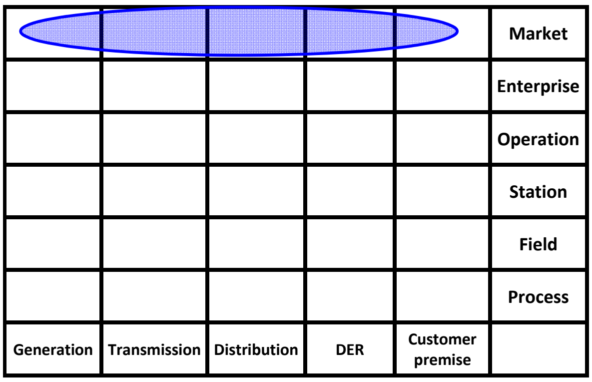
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Trans-Regional / Trans-National network

To interconnect synchronous grids for power interchange, as well as emerging national or even continental scale networks for grid monitoring, inter-tie power flow management, and national or continental scale renewable energy markets (under development networks).



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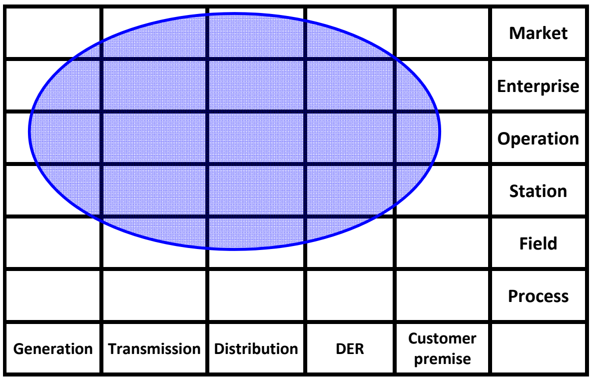
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Wide and Metropolitan Area Network

Network that can use public or private infrastructures;

They inter-connect network devices over a wide area (region or country) and are defined through SLAs (Service Level Agreement).



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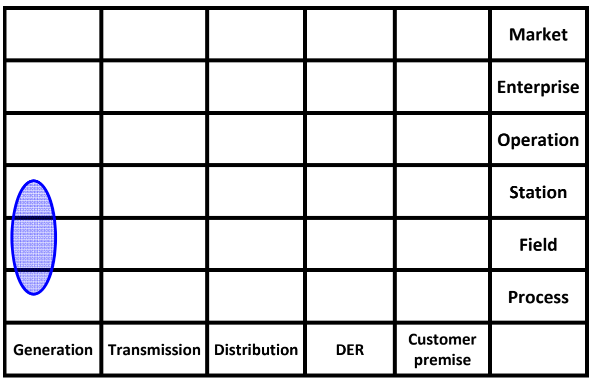
SMART GRIDS COMMUNICATION SUB-NETWORKS

- Industrial Fieldbus Area Network

Networks that interconnect process control equipment mainly in power generation (bulk or distributed) in the scope of smart grids



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